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Best Management Practices for Nutrient and Sediment Retention in Urban Stormwater Runoff

Dianna M. Hogan* and Mark R. Walbridge

ABSTRACT

Stormwater management infrastructure is utilized in urban areas to alleviate flooding caused by decreased landscape permeability from increased impervious surface cover (ISC) construction. In this study, we examined two types of stormwater detention basins, SDB-BMPs (stormwater detention basin-best management practice), and SDB-FCs (stormwater detention basin–flood control). Both are constructed to retain peak stormwater flows for flood mitigation. However, the SDB-BMPs are also designed using basin topography and wetland vegetation to provide water quality improvement (nutrient and sediment removal and retention). The objective of this study was to compare SDB (both SDB-BMP and SDB-FC) surface soil P concentrations, P saturation, and Fe chemistry with natural riparian wetlands (RWs), using sites in Fairfax County, Virginia as a model system. The SDB-BMPs had significantly greater surface soil total P (P_t) concentrations than the RWs and SDB-FCs (831.9 ± 32.5 kg ha^{-1}, 643.3 ± 19.1 kg ha^{-1}, and 652.1 ± 18.8 kg ha^{-1}, respectively). The soil P sorption capacities of SDB-BMPs were similar to the RWs, and were greater than those of SDB-FCs, appearing to result in greater soil P removal and retention in SDB-BMPs compared with SDB-FCs. Increased Fe concentrations and relatively greater amounts of more crystalline forms of Fe in SDB-BMP soils suggested increased sediment deposition compared with RW and SDB-FC soils. Data suggest that SDB nutrient and sediment retention is facilitated in SDB-BMPs. When stormwater management is necessary, use of SDB-BMPs instead of SDB-FCs could foster more responsible urban development and be an appropriate mitigation action for receiving aquatic ecosystems.

The global human population is growing at a rate of approximately 1.3% yr^{-1} (Cincotta et al., 2000). Rapid global population growth is expected to continue (Smail, 2002), particularly in urban areas, dramatically impacting natural landscapes and environmental processes at global, regional, and local scales (Vitousek, 1994; Bolund and Hunhammar, 1999; Walsh, 2000; McKee et al., 2003; Faulkner, 2004). The Washington, DC metropolitan area has experienced rapid expansion since World War II, especially in suburban areas like Fairfax County, VA, just west of Washington, DC (Hooten, 1990; Masek et al., 2000), where the current population of >1 million people is expected to grow at more than 0.7% yr^{-1} through 2025 (County of Fairfax, Virginia, 2004).

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Urbanization is characterized by an increase in impervious surface cover (ISC) as residential, industrial, and commercial areas are developed (Schueler, 1994; Arnold and Gibbons, 1996; Lee and Heaney, 2003). Combined with vegetation removal and land grading, the increases in ISC have the potential to affect regional hydrology and water quality (Watson et al., 1981; Reinelt et al., 1999; Walsh, 2000; Rhodes et al., 2001; Groffman et al., 2003; Faulkner, 2004). These landscape-scale alterations impair stormwater infiltration and ground water recharge, and significantly increase surface runoff during storm events (Schueler, 1994; Schaefer, 1997; Paul and Meyer, 2001; Wissmar et al., 2004). Urban stormwater runoff also carries excess nutrients (i.e., P and N), as well as other pollutants (e.g., trash, sediments, oil and grease, metals, bacteria, and pesticides) (Schueler, 1987; Steuer et al., 1997; Sonstrom et al., 2002; Hope et al., 2004). Nutrient sources in urban catchments include home septic systems, leaky sewer lines, and lawn fertilizers. These nutrients can be mobilized and delivered to aquatic ecosystems (i.e., streams and riparian wetlands) during storm events (Schueler, 1987; Paul and Meyer, 2001). In more highly urbanized watersheds, stormwater management infrastructure redirects runoff captured by artificial channels (e.g., road culverts; curb and gutter systems) into stormwater retention and detention facilities. While this helps to decrease peak stream flow and associated negative effects on stream integrity (Paul and Meyer, 2001), the toxins and excess nutrients carried in urban runoff are not necessarily retained by these stormwater management facilities before the release of stormwaters into area streams (Schueler, 1992). By directing urban runoff toward stormwater management facilities and away from natural wetlands, stormwater management infrastructure can also affect wetland hydrologic and nutrient loads exported from more urbanized watersheds (Reinelt et al., 1999; Ehrenfeld et al., 2003).

A variety of techniques have been developed to manage urban stormwater runoff, including the use of large diameter pipes, porous pavement, subsurface storage (i.e., concrete or plastic underground chambers), infiltration trenches (i.e., basins, depressions, dry wells, rain gardens, and grass filters/swales), rain barrels, and surface basins such as retention ponds, wet or dry detention

Abbreviations: ISC, impervious surface cover; SDB, stormwater detention basin; SDB-BMP, stormwater detention basin-best management practice; SDB-FC, stormwater detention basin–flood control only; RW, riparian wetland; P_w, water-extractable P; P_{ox}, oxalate-extractable P; P_N, sodium hydroxide-extractable P; P_t, total P; Al_{ox}, non-crystalline (oxalate-extractable) Al; Fe_{ox}, non-crystalline (oxalate-extractable) Fe; Al_c, crystalline Al; Fe_c, crystalline Fe; Ca_e, extractable Ca; Al_p, organically bound (pyrophosphate-extractable) Al; Fe_p, organically bound (pyrophosphate-extractable) Fe; PSI, P sorption index; TPSC, total P sorption capacity; PSM, P sorption maxima.

basins, two stage ponds, and natural or constructed wetlands (Schueler, 1987; Galli, 1992; Schueler, 1992; Schaefer, 1997; Sieker and Klein, 1998; Somes et al., 2000; Marsalek and Chocat, 2002; Shammaa et al., 2002). In Fairfax County, retention ponds and detention basins are common stormwater management tools, and receive a significant proportion of the runoff in more highly urbanized landscapes. The hydrology of a 'wet' retention pond is similar to that of a pond or lake ecosystem. The hydrology of a 'dry' detention basin is more similar to a natural wetland, because water levels fluctuate between wet and dry conditions. Initially, County stormwater control programs focused only on flood prevention, but subsequent initiatives developed in response to BMP (best management practice) environmental protection strategies began to include both the decrease of pollutant concentrations carried in stormwater runoff and the protection of area streams against bank erosion, heavy sedimentation, and the loss of biological diversity and habitat (Environmental Coordinating Committee, 2003).

The majority of 'dry' stormwater detention basins in Fairfax County are designed primarily to temporarily detain peak stormwater flows for flood mitigation, and are referred to as SDB-FCs (stormwater detention basin–flood control) in this article. Because SDB-FCs drain quickly after a storm event (i.e., within hours to days), they are usually dry except during storms. SDB-FCs have concrete trickle ditches, are often mowed, and although they may retain some large debris and litter, they are not designed for water quality improvement (i.e., nutrient, sediment, and other pollutant removal and retention). Because the current objectives of stormwater management in Fairfax County include improving water quality and habitat in receiving streams in addition to flood prevention, the feasibility of retrofitting the SDB-FC 'dry' facilities to include nutrient and sediment controls is now being considered (Environmental Coordinating Committee, 2003).

Some 'dry' SDBs are constructed to maintain saturated or shallow flooded soil conditions, and are planted with a variety of wetland plant species. In addition to their roles in flood mitigation, these systems are intended to mimic some of the ecosystem services provided by natural wetlands such as water quality improvement, ground water recharge, and biodiversity support (cf., Johnston, 1991; Walbridge, 1993; Zedler, 2003). These are the facilities developed in response to BMP environmental protection strategies, and are referred to as SDB-BMPs (stormwater detention basin–BMPs) in this paper. The SDB-BMPs do not use concrete trickle ditches, and have topographies designed to slow water input, distributing stormwater runoff over the entire basin. These enhanced detention facilities increase retention time and vegetation filtering, promoting both nutrient removal and sediment retention to improve water quality (Environmental Coordinating Committee, 2003).

We compared P concentrations, P retention capacity, and Fe chemistry in surface soils in six 'dry' SDBs (three SDB-BMPs and three SDB-FCs), with those of 12 natural riparian wetlands (RWs) in Fairfax County, Virginia. We hypothesized that because SDBs are built primarily in highly urbanized areas, and urban runoff is specifically directed toward SDBs, that SDB soils (both SDB-BMPs and SDB-FCs) would exhibit higher soil P concentrations and saturation of P retention functions than RW soils. Due to their similarity in morphology, vegetation, and hydrology, we also hypothesized that SDB-BMPs would be more similar to natural RWs, in terms of soil P retention and Fe chemistries, than to SDB-FCs.

MATERIALS AND METHODS

Study Area and Site Selection

Riparian wetland study sites ($n = 12$) were located in the Piedmont physiographic province in Fairfax County, VA, in suburban watersheds varying in the degree of development as indexed by % ISC (including building footprints, roads, and sidewalks), ranked in three categories: slightly (1.0–6.1%), moderately (8.6–13.3%), and highly (25.1–29.1%) urbanized (Fig. 1). The ISC data were obtained from aerial photography by the Fairfax County Department of Public Works and Environmental Services, and are representative of Fairfax County in 1997. Further details on RW study site selection, and surface soil collection and analysis, are reported in Hogan and Walbridge (2007). The SDB study sites ($n = 6$, three SDB-BMPs and three SDB-FCs) were randomly selected from 16 potential sites in the watersheds of the RWs; Table 1 lists SDB characteristics. County-maintained, regional SDBs are constructed without imported soils and have catchment areas of 40 ha or more. Stormwater management facilities exist primarily in more urbanized watersheds characterized by high % ISC, accounting for the different distribution of RW vs. SDB study site locations (Fig. 1).

Soil Collection and General Analysis

Soil cores (0–15 cm), obtained by driving a 4 cm diam. PVC pipe with a sharpened edge into the ground after brushing away surface litter, were randomly collected from each site during summer 2002 (USEPA, 1989). At each site, four randomly located 4 by 4 m plots were established and divided into four 2 by 2 m subplots. One soil core was randomly collected within each subplot ($n = 4$ per plot), and composited by plot to produce four distinct samples per study site. Soils were stored in polyethylene bags, kept on ice in the field, and stored at 4°C (field moist) in the laboratory. Soils were homogenized by hand, removing coarse roots and rocks. Extractions for P, Al, and Fe, and P sorption isotherms were begun within 24 h on duplicate subsamples.

Soil Physical and Phosphorus Analyses

Soil pH was estimated after a 10 min equilibration in a 1:2 soil/deionized water slurry. Texture was determined by the hydrometer method (Bouyoucos, 1962). Moisture content was determined by oven-drying soil aliquots at 90°C to a constant mass. Bulk density was calculated as soil dry mass/core volume. Water-extractable P (P_w), an estimate of potential P release from soil to water, was estimated by the method of Sissingh (1971). Oxalate-extractable P (P_{ox}), an estimate of total P associated with oxalate-extractable Al and Fe (Al_{ox} and Fe_{ox}) (Van der Zee et al., 1988), was estimated in conjunction with Al_{ox} and Fe_{ox}. Sodium hydroxide-extractable P (P_N), an estimate of P associated with soil Al and Fe minerals, was estimated by the methods of Bache and Williams (1971) and

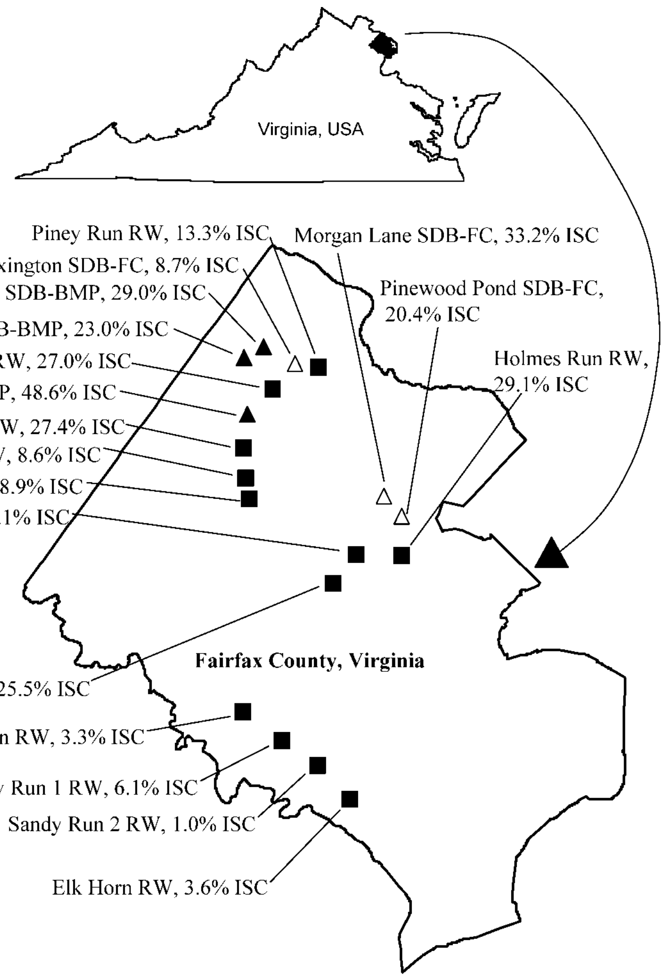

Fig. 1. Map of Virginia showing the location of Fairfax County (in black), and the stormwater detention basin (SDB-BMP and SDB-FC) and the natural riparian wetland (RW) study site locations in Fairfax County, VA. The triangles represent the locations of the six stormwater detention facilities (three SDB-BMPs ▲, three SDB-FCs △) and the dark squares (■) represent the locations of the 12 RWs (RW data from Hogan and Walbridge [2007]).

Hedley et al. (1982). Phosphorus extracts were analyzed colorimetrically as orthophosphate by the method of Murphy and Riley (1962), using a Technicon II Autoanalyzer (Bran and Luebbe, Inc., 1989, Method Number 696-82W, 1B) except for P_{ox}, which was analyzed by inductively coupled plasma spectroscopy (ICP) (Novozamsky et al., 1986). Total P (P_t) was determined by sulfuric acid, potassium sulfate, and mercuric oxide digestion, using a Technicon BD40 block digester (Williams et al., 1970; Walbridge, 1991) and analyzed colorimetrically using a Technicon II Autoanalyzer (Bran and Luebbe, Inc., 1989, Method Number 696-82W, 1A and 1C).

Aluminum, Iron, and Calcium

Soil non-crystalline (amorphous), crystalline, and total Al and Fe content were estimated by the methods of USDA-SCS (1972), Boero and Schwertmann (1989), and Hsu (1991), as modified by Darke and Walbridge (1994). Exchangeable Ca (Ca_e) was estimated by the method of Thomas (1982). Organically bound (pyrophosphate-extractable) Al and Fe (Al_p and Fe_p) were estimated by the method of Parfitt and Childs (1988) with superfloc (0.5 mL of a 1.0 g kg^{-1} solution) added to facilitate sedimentation (Schuppli et al., 1983). Soil

Table 1. Characteristics of the stormwater detention basin (three SDB-BMP and three SDB-FC) study sites. Sites are named after the area in which they were developed.

Site	Year built/type	Soil classification†	Soils series†	Watershed and stream
Reston 913	1960, enhanced to BMP 1980	Typic Hapludults	Glenelg	Difficult Run, Colvin Run
North Village	1992 BMP	Aquic Fragiudults	Glenville	Difficult Run, Piney Run
Pinewood Pond	1994 BMP	Aquic Fragiudults	Glenville	Cameron Run, Holmes Run
Lexington	1982 FC	Typic Dystrudepts	Manor	Difficult Run, Piney Run
Morgan Lane	1988 FC	Fluvaquentic Endoaquepts/ Fluvaquentic Dystrudepts	Likely Hatboro/Codorus	Cameron Run, Holmes Run
Reston Northern Sector	1992 FC	Aquic Fragiudults	Glenville	Difficult Run, Piney Run

† Soils data from Porter et al. (1963), Environmental and Facilities Review Division (1990), Natural Resources Conservation Service (2004), and Kokales (personal communication, 2004).

Al, Fe, and Ca concentrations were determined using a PerkinElmer 5100PC atomic absorption spectrometer and standard methods (PerkinElmer, 1982) except for Al_{ox} and Fe_{ox}, which were analyzed by ICP (Novozamsky et al., 1986).

Phosphorus Sorption Capacity

Phosphorus sorption capacity was estimated by the decrease in orthophosphate in a 24-h equilibration with 25 mL of a 0, 16, 33, 130, or 260 mg P L^{-1} KH_2PO_4 solution in 0.01 M $CaCl_2$ (Bache and Williams, 1971); orthophosphate concentrations were analyzed as above. Phosphorus sorption isotherms were constructed using the methods of Bache and Williams (1971), as modified by Richardson (1985) and Walbridge and Struthers (1993). A single-point P sorption index (PSI) based on P sorbed from the 130 mg P L^{-1} solution, was calculated as $x/\log c$, where x = P sorbed in mg P/100 g soil, and c = the equilibrium P concentration in μM L^{-1} (Bache and Williams, 1971). Previously sorbed P was estimated using P_N (described above); total P sorption capacity (TPSC) was calculated as $(x + P_N)/\log c$. Theoretical P sorption maxima (PSM) were calculated as the y-intercept of the linear plot of x vs. $(x/c)^{1/2}$ using a modified version of the Langmuir equation (Bache and Williams, 1971) to account for the decrease in free energy of adsorption with increasing surface coverage (Kuo, 1988). Theoretical PSM were corrected for soil bulk density to compare total P sorption potentials (TPSP) across sites. Saturation of soil P sorption capacity was estimated as the molar ratio of $P_{ox}/[(Al_{ox} + Fe_{ox})/2]$, and by comparison of P_{ox} and P_N concentrations with TPSP (Van der Zee and Van Riemsdijk, 1988; Beauchemin and Simard, 1999; del Campillo et al., 1999; Kleinman et al., 1999; Pote et al., 1999; Hughes et al., 2000; Peltovuori et al., 2002).

Statistical Analyses

Significant differences in physical and chemical properties were determined by analysis of variance (ANOVA) and the Student-Newman Keuls multiple comparison test (Sokal and Rohlf, 1995). Relationships between the PSI or TPSC and soil characteristics were analyzed by both single factor and stepwise multiple regression. Analyses were performed using JMP (SAS, 2002) and Microsoft Excel 2000 (Microsoft Corporation, 2000). Significant differences were considered at $p \leq 0.05$ and $p \leq 0.10$ as indicated in the text with the exception of the stepwise multiple regression where significant differences were considered at $p < 0.25$ to enter and $p < 0.10$ to leave the model; SAS (2002) recommends this to avoid inclusion of variables that do not contribute to model predictive power.

RESULTS

Soil Physical and Chemical Characteristics

Stormwater detention and RW soils differed significantly in pH (5.9 and 5.2, respectively; Table 2). The SDB-BMP soils had significantly greater silt content and lesser sand content than either the SDB-FC or RW soils. Clay content, potentially important for P sorption capacity, was similar in SDB-BMP and RW soils, and significantly lower in SDB-FC soils (Table 2). The SDB-BMP soils had significantly greater P_{ox} and P_t concentrations than either the SDB-FC or RW soils, and significantly greater P_N concentrations than RW soils (Table 2).

Mean concentrations of Al_p, Al_{ox}, and Al_t were all significantly greater in RW soils, as compared with the SDB-BMP and SDB-FC soils (Table 3). Mean concentrations of Ca_e, Fe_c, and Fe_t were all significantly greater in SDB-BMP soils, as compared with the SDB-FC and RW soils (Table 3). With the exception of Al in the SDB-FC, the majority of both Al and Fe present were in crystalline form (Table 3). Concentrations of Fe_c and Fe_t in SDB-BMP soils were most similar to RWs in highly urbanized watersheds; Fe_c and Fe_t concentrations in SDB-FC soils were most similar to those of RWs in moderately urbanized watersheds (Fig. 2).

Table 2. Soil physical and chemical properties in surface soils (0–15 cm) of the stormwater detention basin (three SDB-BMP and three SDB-FC) and natural riparian wetland (RW) study sites. Lowercase letters (a, b, and c) indicate significant differences between means of SDB-BMPs, SDB-FC, and RWs ($p < 0.05$). Data are means with standard errors in parentheses, except for pH and N/P ratios, which are means with ranges in parentheses.

Parameter	SDB-BMPs (n = 3)	SDB-FCs (n = 3)	RWs (n = 12)†
pH	5.9 (5.5–6.4)a	5.9 (5.8–6.1)a	5.2 (4.7–5.9)b
Bulk density (g cm^{-3})	1.02 (0.01)b	1.17 (0.01)a	1.11 (0.00)ab
Sand (%)	19.7 (4.2)c	48.7 (11.2)a	34.9 (3.5)b
Silt (%)	57.5 (3.1)a	37.0 (8.1)b	40.8 (2.5)b
Clay (%)	22.8 (2.4)a	14.3 (3.2)b	24.2 (1.4)a
P_w (kg ha^{-1})‡	1.7 (0.3)	1.6 (0.4)	0.8 (0.2)
P_{ox} (kg ha^{-1})§	256.3 (22.7)a	189.0 (11.6)b	194.0 (10.0)b
P_N (kg ha^{-1})¶	178.1 (11.0)a	136.2 (9.8)ab	135.0 (7.7)b
P_t (kg ha^{-1})#	831.9 (32.5)a	652.1 (18.8)b	643.3 (19.1)b

† RW data from Hogan and Walbridge (2007).
‡ P extracted by water.
§ P extracted by acid ammonium oxalate at pH = 3.0.
¶ P extracted by 0.1 M sodium hydroxide.
# Total P as found by sulfuric acid/potassium sulfate/mercuric oxide digestion.

Phosphorus Retention

The P sorption capacities of SDB-BMP and RW soils were similar, and were significantly greater than the P sorption capacities of SDB-FC soils (Fig. 3). Soil P sorp-

Table 3. Soil aluminum and iron concentrations by selective dissolution and exchangeable calcium in surface soils (0–15 cm) of the stormwater detention basin (SDB-BMP and SDB-FC) and natural riparian wetland (RW) study sites. Lowercase letters a and b indicate significant differences between SDB-BMPs, SDB-FCs, and RWs ($p < 0.05$). Data are means with standard errors in parentheses.

Parameter	SDB-BMPs (n = 3)	SDB-FCs (n = 3)	RWs (n = 12)†
	kg ha^{-1}		
Al_p‡	703.3 (43.8)b	713.8 (40.9)b	997.0 (48.3)a
Al_{ox}§	1201.2 (31.5)b	1015.2 (78.9)b	1431.4 (44.7)a
Al_c¶	1760.7 (317.2)ab	1005.8 (95.5)b	2678.4 (206.0)a
Al_t#	2961.9 (302.2)b	2021.0 (150.1)b	4109.8 (235.0)a
Fe_p‡	5152.9 (208.6)	4299.9 (302.2)	5072.5 (262.7)
Fe_{ox}§	8495.8 (569.0)	7107.8 (408.7)	7498.9 (375.5)
Fe_c††	40 358.1 (2094.9)a	22 204.2 (1413.0)b	24 721.3 (1493.3)b
Fe_t‡‡	48 853.9 (1882.5)a	29 312.1 (1586.1)b	32 220.1 (1715.8)b
Ca_e§§	994.5 (101.0)a	431.2 (18.8)b	473.1 (36.6)b

† RW data from Hogan and Walbridge (2007).
‡ Organically bound Al or Fe (Al or Fe extracted by 0.1 M sodium pyrophosphate).
§ Non-crystalline plus organically bound Al or Fe (Al or Fe extracted by 0.2 M acid ammonium oxalate at pH = 3.0).
¶ Crystalline Al (Al extracted by 0.1 M sodium hydroxide following 0.2 M acid ammonium oxalate extraction).
# Total free Al (Al extracted by 0.2 M acid ammonium oxalate plus Al extracted by 0.1 M sodium hydroxide).
†† Crystalline Fe (DCB Fe minus oxalate-extractable Fe).
‡‡ Total free Fe (DCB-extractable).
§§ 1.0 M ammonium acetate-extractable (exchangeable) Ca.

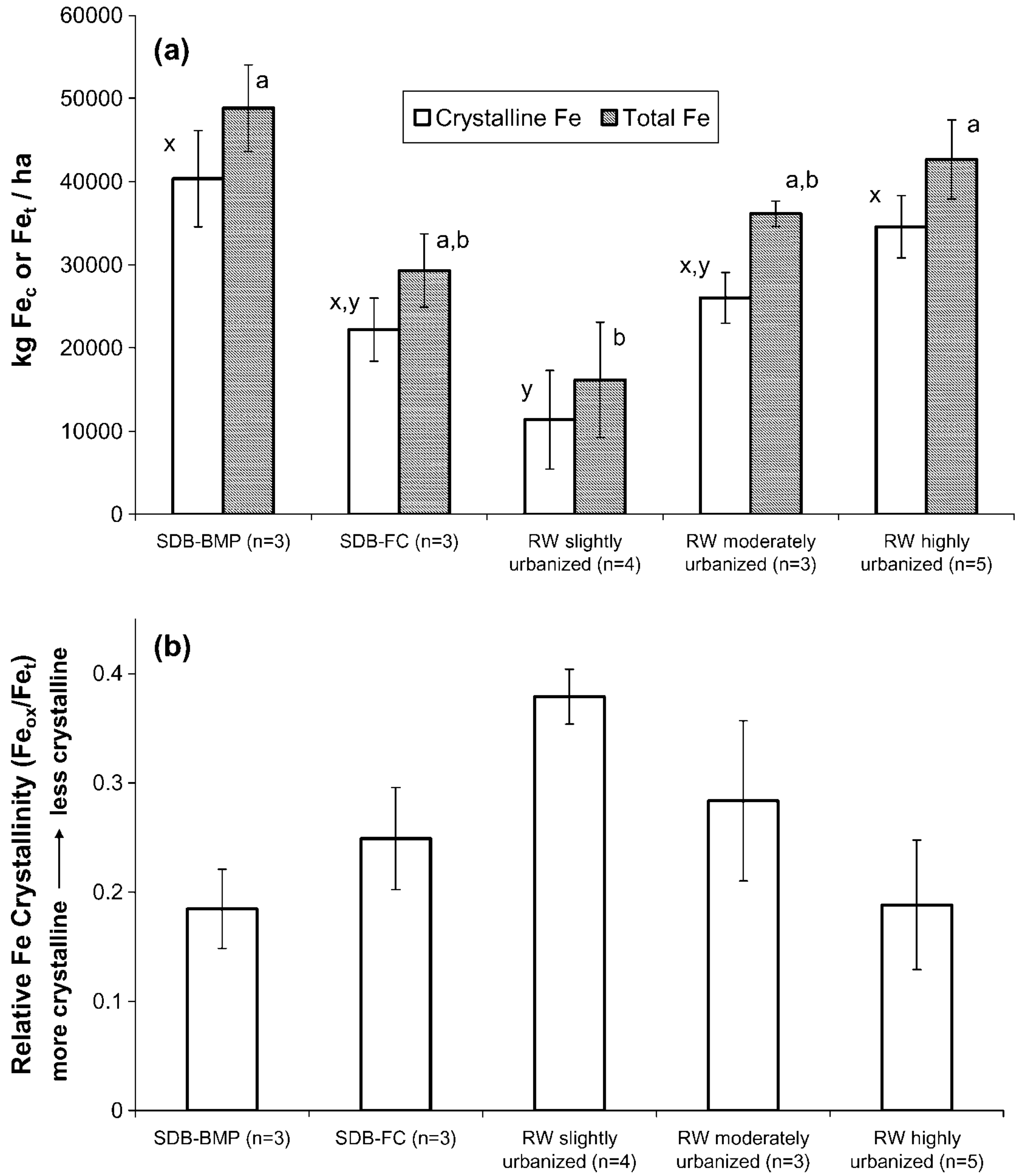

Fig. 2. Stormwater detention basin (SDB-BMP and SDB-FC) and riparian wetland (RW) soil (a) crystalline and total Fe (Fe_c and Fe_t) and (b) relative Fe crystallinity (indexed as Fe_{ox}/Fe_t). The 12 natural RWs (RW data from Hogan and Walbridge [2007]) are grouped as a function of % impervious surface cover (ISC) in their surrounding watershed into three categories: slightly (1.0–6.1%), moderately (8.6–13.3%), and highly (25.1–29.1%) urbanized (Fig. 1). Error bars represent ± 1 SE and lowercase letters x and y or a and b indicate significant differences ($p < 0.05$) for crystalline or total Fe, respectively.

tion capacities of chloroform-sterilized soils were similar to those of nonsterilized soils (Hogan, 2005). The PSI (a single point phosphorus sorption index) and TPSC (including previously sorbed P) were highly correlated in the SDB-FC soils ($r^2 = 0.99$, $p > 0.06$) and the RW soils ($r^2 = 0.89$, $p > 0.0005$), but not in SDB-BMP soils ($r^2 = 0.68$, $p > 0.38$), likely due to the Reston 913 SDB-BMP site, where PSI increased, but NaOH-extractable P (P_N) did not.

Based on both single factor and stepwise multiple regression, pyrophosphate-extractable Fe (Fe_p) was the single most important predictor of TPSC in SDB-BMP soils ($r^2 = 0.99$, Table 4). Stepwise multiple regression also identified only a single factor (Fe_t) as the best predictor of P sorption capacity in SDB-BMP soils ($r^2 = 0.94$). In contrast, forms of Al (Al_t and Al_c) were the most important single predictors of P sorption capacity in SDB-FC soils (Table 4). Stepwise multiple regression identified Al_c alone as the best predictor of P sorption capacity in SDB-FC soils, as indexed by either PSI or TPSC ($r^2 = 0.99$ and 0.98, respectively). When considering SDB-BMP, SDB-FC, and RW soils together, Fe_p was the best predictor of P sorption capacity using the PSI ($r^2 = 0.59$) and ($Al_{ox} + Fe_{ox}$) was the best single predictor when accounting for previously sorbed P ($r^2 = 0.65$) (Table 4). Stepwise multiple regression identified

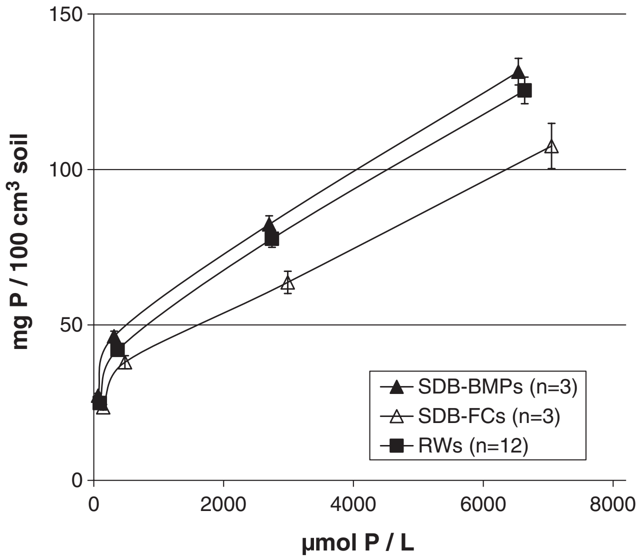

Fig. 3. Phosphorus sorption isotherms for the stormwater detention basin (SDB-BMPs and SDB-FCs) in comparison with the natural riparian wetland (RW) soils (RW data from Hogan and Walbridge [2007]). SDB-BMP soils are shown by closed triangles (▲), SDB-FC soils are shown by open triangles (△), and RW soils are indicated by dark squares (■). The figure illustrates the amount of P sorbed following a 24-h equilibration with initial P concentrations of 16, 33, 130, and 260 mg P L^{-1} plotted as a function of the P remaining in solution following equilibration. Error bars indicate ± 1 SE.

a two-term model based on Fe_p and clay ($r^2 = 0.68$) for predicting PSI, and a three-term model based on Al_{ox} + Fe_{ox}, Al_c, and Al_p ($r^2 = 0.83$) for predicting TPSC.

Phosphorus that has been sorbed via Al_{ox} and Fe_{ox} can be estimated by P_{ox}. When P_{ox} exceeds $(Al_{ox}+Fe_{ox})/2$, expressed as mol kg^{-1}, the soil is considered to be P saturated (Van der Zee and Van Riemsdijk, 1988; del Campillo et al., 1999). Using this criterion, no significant differences were found for soil P saturation between SDB-BMP, SDB-FC, and RW soils (8.1, 7.4, and 8.0% P saturated, respectively).

The SDB-FC soils had generally lower PSM and TPSP than SDB-BMP or RW soils (Table 5). As an alternate way to estimate soil P saturation, P_N and P_{ox} were expressed as a percentage of the theoretical total P sorption potential (Table 5). By this method, soil P saturation for P_N and P_{ox} was generally greater in SDB-BMP and SDB-FC soils as compared with RW soils (Table 5).

DISCUSSION

Stormwater management was originally designed solely for flood control. More recently, the negative effects of increased pollutant levels in urban stormwater runoff have been recognized, and construction of SDBs as SDB-BMP systems, with nutrient, sediment, and toxin retention capacities began, to help ameliorate the degradation of receiving streams and estuaries downstream (Galli, 1992; Schueler, 1992; Sieker and Klein, 1998; Carleton et al., 2000; Heitz et al., 2000; Somes et al., 2000; Environmental Coordinating Committee, 2003). Thus it is not surprising that the SDB-BMP soils in this study had significantly greater soil P concentrations than RWs, but the SDB-FC soils did not (Table 2). Higher soil P concentrations were consistent with higher soil P retention capacities in SDB-BMP than in SDB-FC soils (Fig. 3, Table 5).

Although the SDB-BMPs were similar in P sorption capacity to the natural RWs (Fig. 3, Table 5), different soil factors emerged as important predictors of P sorption potential (Table 4). Mean Al concentrations were

Table 4. Coefficients of determination (r^2) between the P sorption index (PSI), or total P sorption capacity (TPSC), and soil characteristics, in the stormwater detention basin (SDB-BMP and SDB-FC) and natural riparian wetland (RW) surface soils (0–15 cm), based on single factor regression.

	PSI†				TPSC‡			
Parameter	SDB-BMPs (n = 3)	SDB-FCs (n = 3)	RWs (n = 12)§	All sites (n = 18)	SDB-BMPs (n = 3)	SDB-FCs (n = 3)	RWs (n = 12)§	All sites (n = 18)
Al_p¶	0.06	0.78	0.33**	0.25**	0.56	0.85	0.47**	0.44**
Al_{ox}#	0.09	0.38	0.46**	0.28**	0.61	0.29	0.61**	0.46**
Al_c††	0.03	0.99**	0.70**	0.40**	0.17	0.98*	0.75**	0.59**
Al_t‡‡	0.05	0.98*	0.73**	0.42**	0.14	0.95	0.81**	0.63**
Fe_p¶	0.61	0.89	0.72**	0.59**	0.99**	0.94	0.68**	0.62**
Fe_{ox}#	0.00	0.49	0.65**	0.48**	0.33	0.58	0.83**	0.62**
Fe_c§§	0.75	0.02	0.04	0.05	0.18	0.00	0.19	0.14
Fe_t¶¶	0.94	0.00	0.12	0.11	0.43	0.01	0.32*	0.23**
Al_{ox} + Fe_{ox}##	0.00	0.51	0.66**	0.50**	0.35	0.60	0.85**	0.65**
Ca_e†††	0.00	0.79	0.02	0.00	0.36	0.86	0.02	0.00
Clay (%)	0.05	0.89	0.44**	0.40**	0.14	0.94	0.56**	0.51**

*, ** Asterisks indicate factors significant at $p \leq 0.05$ (**) and $p \leq 0.10$ (*).
† x/log c where x = mg P sorbed/100 g soil and c = μM P remaining in solution after 24-h equilibration with 130 mg P L^{-1}.
‡ $x + P_N$/log c where P_N is P extracted by 0.1 M sodium hydroxide, x = mg P sorbed/100 g soil and c = μM P remaining in solution after 24-h equilibration with 130 mg P L^{-1}.
§ RW data from Hogan and Walbridge (2007).
¶ Organically bound Al or Fe (Al or Fe extracted by 0.1 M sodium pyrophosphate).
# Non-crystalline plus organically bound Al or Fe (Al or Fe extracted by 0.2 M acid ammonium oxalate at pH = 3.0).
†† Crystalline Al (Al extracted by 0.1 M sodium hydroxide following 0.2 M acid ammonium oxalate extraction).
‡‡ Total free Al (Al extracted by 0.2 M acid ammonium oxalate plus Al extracted by 0.1 M sodium hydroxide).
§§ Crystalline Fe (DCB Fe minus oxalate-extractable Fe).
¶¶ Total free Fe (DCB-extractable).
Non-crystalline plus organically-bound Al + Fe (Al + Fe extracted by 0.2 M acid ammonium oxalate at pH = 3.0).
††† 1.0 M ammonium acetate-extractable (exchangeable) Ca.

Table 5. Stormwater detention basin (SDB-BMP and SDB-FC) and natural riparian wetland (RW) surface soil (0–15 cm) P sorption maxima (PSM) with the corresponding correlation coefficients in parentheses, calculated using a modified Langmuir equation (Bache and Williams, 1971); total P sorption potentials (TPSPs) with standard errors in parentheses; and soil P saturation for oxalate-extractable P (P_{ox}) and sodium hydroxide-extractable P (P_N), calculated as a percentage of theoretical TPSP, with standard errors in parentheses.

Parameter	PSM	TPSP	% Soil P saturation	
			P_{ox}	P_N
	mg P/100 g dry soil	kg P ha^{-1}		
SDB-BMPs (n = 3)	130.2 (0.78)	1988.1 (57.0)	12.8 (3.5)	9.0 (1.2)
SDB-FCs (n = 3)	107.6 (0.79)	1685.5 (250.3)	11.2 (0.1)	8.0 (0.8)
RWs (n = 12)†	119.7 (0.80)	1913.8 (129.6)	9.9 (0.9)	7.0 (0.7)

† RW data from Hogan and Walbridge (2007).

greater in the RW than in the SDB soils, where Al concentrations were better predictors of P sorption capacity (Al_t $r^2 = 0.73$, $Al_{ox} + Fe_{ox}$ $r^2 = 0.85$, Tables 3 and 4). The greater overall predictive ability of $Al_{ox} + Fe_{ox}$ ($r^2 = 0.65$) as indexed by TPSC (Table 4) is consistent with del Campillo et al. (1999) and Maguire et al. (2001), who found Fe and Al oxides are important for the maintenance of soil P sorption capacity in The Netherlands, Ireland, and the U.S. mid-Atlantic Coastal Plain. In comparison, SDB-BMP soils were characterized by greater concentrations and importance of Fe (as opposed to Al) in predicting P sorption potential (Fe_p $r^2 = 0.99$ by TPSC, Tables 3 and 4). Pyrophosphate-extractable Fe (Fe_p) includes ferrihydrite, an amorphous Fe mineral that may be important in soil P sorption (Parfitt and Childs, 1988; Walbridge and Struthers, 1993; Kaiser and Zech, 1996).

Urbanization greatly increases sediment availability and movement into aquatic ecosystems (Schueler, 1994; Reinelt et al., 1999; Paul and Meyer, 2001; Groffman et al., 2003); this increased sediment input could help sustain the P retention capacity of SDB-BMP soils by bringing in more Fe from upland sources. Increased Fe concentrations and a relatively greater amount of more crystalline forms of Fe were observed in the SDB-BMP soils, similar to RWs in highly developed watersheds (Table 3, Fig. 2 a, b). These RW trends were also explained by increased sedimentation of crystalline forms of Fe from watershed sources as a consequence of intensifying urban landscape erosion and development (Hogan and Walbridge, 2007).

As hypothesized, in comparison to RWs and SDB-BMPs, SDB-FC soils appear to have a lesser capacity to retain P, as evidenced by their lower P sorption potentials (Fig. 3, Table 5). Because SDB-FC systems focus on flood control for less frequent, greater intensity rainfall events, they often do not have the opportunity to function for nutrient or sediment retention. The majority of stormwater runoff is contained in concrete trickle ditches, where it is prevented from interacting with the soil surface, except during large, infrequent rain events, when these ditches overflow. Smaller, more frequent rainfall-runoff events, and the first flush at the onset of larger storms, carry the major portion of pollutants in urban stormwater runoff (Heitz et al., 2000; Lee and Bang, 2000; Shammaa et al., 2002; Hope et al., 2004). Both detention time and contact with soil and vegetation are key elements of the ability of SDBs to provide surface water quality benefits (Johnston, 1991; Schueler, 1992; Somes et al., 2000).

Similar SDB-FCs in Prince George's County, Maryland, were also shown to be unable to provide water quality benefits or protection from stream channel erosion; the use of BMPs (including artificial marshes and extended detention dry facilities), and the conversion of existing systems into BMPs, was recommended (Galli, 1992). Likewise, the use of decentralized planted infiltration troughs instead of centralized stormwater treatment plants was recommended in Berlin, Germany, to enhance ground water recharge, flood protection, and suspended and soluble pollutant removal with lower overall costs (Sieker and Klein, 1998). Carleton et al. (2000) converted a SDB in Virginia to a BMP system by simply adding an outlet weir, resulting in increased basin flooding, retention time, and the establishment of volunteer wetland vegetation. This low-cost retrofit added water quality improvement at an older SDB not originally designed for that function. Several other studies cite design, size, retention time, wetland vegetation, and the use of basin topography to promote shallow, nonchannelized flow, as key factors for pollutant removal efficiency and water quality improvement, and minimizing the impact of stormwater runoff on receiving waters (Kantrowitz and Woodham, 1994; Pettersson, 1998; Tilley and Brown, 1998; Heitz et al., 2000; Bonilla-Warford and Zedler, 2002; Shammaa et al., 2002).

The SDB-BMPs in this study are characterized by topography intended to direct inflow waters across the entire basin, increasing retention time and maximizing contact between urban runoff and soils. However because of their intended function, they receive directed runoff that can contain high concentrations of sediment, nutrients, and toxins (i.e., hydrocarbons, metals, and pesticides) from extensively urbanized areas. Total P sorption capacity and PSI were not significantly correlated in the SDB-BMP study sites ($r^2 = 0.68$, $p > 0.38$), due to one study site, Reston 913, in which the greater PSI did not result in greater soil P sorption (PSI increased, but NaOH-extractable P did not). The soils in the Reston 913 study site were coated with hydrocarbons (black oil), leaving permanent black stains on lab plastic ware. This SDB-BMP functions to drain several large parking lots and roadways, and these inputs may affect the ability of this site to retain nutrients received in stormwater. Other stormwater management systems are designed to intercept hydrocarbons from parking lot runoff, and may be better suited to manage this pollutant by use of skimmers and filtration systems, potentially retaining oil, before use of constructed wetlands for subsequent treatment of runoff (Sonstrom et al., 2002).

Historically, natural wetlands were well suited for water quality improvement. However, urbanization results in increased pollutant loads in runoff, and alters the physical landscape, often redirecting surface water flows away from natural wetlands. Because of this, natural wetlands may no longer function effectively to improve water quality or mitigate downstream flooding, necessitating the use of modified systems to manage urban stormwater runoff. Combined with use of individual property management protocols such as rain gardens and rain barrels, treatment of stormwater in BMP facilities could promote more responsible urban development and be an appropriate mitigation action, allowing cleaner water to enter local streams and downstream aquatic ecosystems.

CONCLUSIONS

Protecting and restoring the physical, chemical, and biological integrity of riparian areas has not always been a priority for stormwater management in urban watersheds. Although by definition, any stormwater management program will alter hydrologic flow paths in the watershed, SDBs and stormwater management plans can be designed to minimize or mitigate adverse physical and biological effects on RWs, streams, and downstream ecosystems. Stormwater management plans may be intended solely to prevent flooding (i.e., SDB-FC systems), or may be constructed as BMP sites, which, in addition to flood water management, may also avoid streambed erosion and downcutting and provide wetland ecosystem services including water quality improvement (nutrient and sediment removal and retention). In this study, soil P sorption capacities of SDB-BMPs were similar to those of natural RWs, and were greater than those of SDB-FCs, appearing to result in greater soil P removal and retention in SDB-BMPs as compared with SDB-FCs. In addition, increased Fe concentrations and relatively greater amounts of more crystalline forms of Fe in SDB-BMP soils suggested increased sediment deposition, potentially helping to sustain SDB-BMP soil P retention capacity by bringing in more Fe from upland sources.

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